Processing of visuo-auditory prosodic information in cochlear-implanted patients deaf patients

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Abstract

Linguistic prosody is a poorly treated subject in cochlear-implanted (CI) patients. Our study investigated how CI patients integrate visual and auditory prosodic cues. The results demonstrate that CI patients are not better performers than normal-hearing subjects (NHS) in discriminating visual prosodic information, but that they have better multi-sensory integration skills than controls. This study confirms the importance of viuso-auditory integration in CI user for speech comprehension completed by multimodal prosodic information.

Key words: audiovisual prosody, cochlear implant, multi-sensory gain

1. Introduction

Cochlear implantation (CI) is a rehabilitative neuroprosthesis destined for individuals with severe to profound bilateral hearing loss. This CI technology partially restores auditory function to enable speech comprehension, via an electrical stimulation of the auditory nerve [1]. Indeed, the auditory information given by the implant to the brain is degraded as it provides poor spectral information while preserving the temporal structures of sound [2]. Therefore the CI adequately restores the sound envelope while the formants are spectrally and temporally degraded [3]. Hence, patients compensate using the visual sensory channel leading to audio-visual integration.

It is a well known that speech is not just constructed from linguistic units but also from supra-linguistic characteristics, such as prosody, which in turn depends on changes in frequency, amplitude, duration and rhythm. Prosody is often defined as the "*melody of speech"* [4], it is associated to the emotional content of the speech and from a linguistic point of view, it aids in distinguishing a statement from a question. Unfortunately, these prosodic structures are poorly coded by the implant due to the degraded spectral information [5]. This induces in CI patients difficulties in identifying gender, vocal identity, emotions carried by the voice as well as musical information [6] [7]. In cochlear implanted patients, the deficits in discrimination of the fundamental frequency [8] induces deficits for auditory speech prosody discrimination especially if they do not have any residual hearing [5] [9]. Nonetheless, research has shown that visual information plays a crucial role, post cochlear implantation, in the recuperation of speech comprehension as patients use visual speech cues (i.e. lip reading) to aid their comprehension of auditory stimuli [3] [10] [11]. Since speech is a well-established multisensory stimulus, it is natural to assume prosody is multisensory and has visual correlates and in fact certain facial movements are distinctly associated with auditory prosodic cues within a sentence [12]. For example: head movements are correlated with variations in the fundamental frequency of speech (pitch) and amplitude [13].Further, the stressed word in a sentence can be identified solely on visual prosodic cues [13]. Further support for the presence of visual correlates of prosody emanate from Foxton et al., (2010) [14], who demonstrated that when participants are faced with congruence between visual and auditory prosodic cues, they perceive auditory prosodic cues as stronger. Hence, in bimodal stimulation, visual prosody significantly influences the perception of auditory prosody thereby facilitating cross modal perception of prosody. Further, several studies have stated that when visual information is available the perception of prosody is facilitated [15] [13] [12].

1.1. Aims of the study

The aim of this study was to investigate how CI patients process visual prosodic cues compared to normal hearing subjects (NHS) based on the assumption that CI patients are have developed visual compensatory skills making them better visual integrators for speech related information. Post-implantation, patients maintain supra-normal performances through time, in their speech reading skills compared to NHS, suggesting that the visual speech information counteract the degraded spectral information [16].Thereby suggesting the possibility of an adaptive synergy between visual and auditory information enabling better audio-visual gain that that observed in NHS. The research questions posited are the following:

- Do cochlear implanted patients benefit from auditory visual cues in the presence of prosodic ambiguity?
- Are CI patients better audio-visual integrators than NHS?

2. Materials and methods

2.1. Subjects

19 cochlear implanted (CI) patients and 30 normal hearing subjects (NHS) took part in this behavioural study on prosody. All NHS were native French speakers with self-reported normal hearing and had self-reported normal or corrected-to-normal vision. CI patients were adults with a bilateral profound hearing loss acquired post-lingually due to diverse aetiologies. The duration of sensory deprivation varies

10.21437/AVSP.2017-16

according to each participant. The patients were either unilaterally or bilaterally implanted. Those implanted unilaterally had no residual hearing successfully compensated with hearing aids. At the time of this study all patients had more than 60% comprehension of dissyllabic words, indicating patients with good auditory recuperation and adaptation to the implant.
The age range of patients was comprised between 20 and 84 years with a mean of 57,8 ± 16,4 years old, 9 were women and 10 were male. Meanwhile the NHS group was composed of 20 women and 16 men with varying age ranges from 20-64 years of age with a mean age of 22,4 ± 2,6 years old.
All participants provided full informed consent prior to inclusion in this research protocol.

2.2. Stimuli

The stimuli presented to the participants were videos of unpunctuated spoken sentences, which could be posited to the subjects as either a question or a statement through the use of prosody. These sentences were allocated to three presentation conditions: visual only (V), auditory only (A) and audio-visual (AV).

The videos were recorded with a professional digital camera (specs of the video). Each sentence was then isolated from the main recording using window moviemaker® and the final stimuli was created. In order to diminish the language component of the task the unpunctuated written sentence was presented prior to the video.

2.3. Strategies inherent to this study

In order to better compare the data obtained from CI patients and NHS, we controlled certain parameters in the creation of the stimuli. Firstly, we asked the two French actors to reduce their facial expressions to diminish the natural visual cues associated with a question or a statement, thereby, increasing the difficulty in distinguishing these two linguistic items. This was also done to avoid a ceiling effect in the performances of CI patient as previous research has shown enhanced visual capacities in this patient population due to the crossmodal compensation mechanisms.
Secondly, for the NHS, we degraded the auditory information using a 8 canals vocoding system, for the auditory and audio-visual conditions. The vocoding simulates the process that occurs in a cochlear implant as the temporal information of the sound is preserved but the fine acoustical structures are degraded [3]. The use of vocoding avoids the ceiling effect obtained if NHS are presented with normal auditory stimuli. Furthermore controlling these parameters, through the use of these two strategies, will permit a better comparison between CI patients and normal hearing controls when comparing each modality.

2.4. Stimuli presentation

For each condition, the participants are presented with a fixation cross, followed by a written sentence (without any punctuation) then another fixation cross and the video in accordance with the condition presented (V, A, VA). At the end of the video, the subjects have to make a judgement on the prosodic form of the sentence: was it a question or a statement?
The stimuli were presented through Matlab®, on a portable PC, speakers were located beside the computer screen and the volume was calibrated to be between 55 and 65dB. The order of the stimuli presentation, within each condition was random. The visual condition was presented first for each subject, followed by the audio-visual and auditory conditions, which varied alternatively in their presentation order.

2.5. Data analysis

The behavioural data was collected in terms of raw performance, i.e. the percentage of correct responses, and analysed using excel®, matlab® and R®. Regarding each condition presented to the participants, a comparative analysis was carried out between the two subject groups. For this a mixed linear effect model was used to compare the percentage of correct responses. Additionally, the raw data was also transformed into d'prime values, in order to obtain the sensibility value and counteract the decisional bias of each individual. Furthermore, we calculated the visuo-auditory gain of CI patients to the one obtained by NHS. The VA gain was calculated individually by normalizing the performances in the VA condition with respect to the best unimodality (either visual or auditory). This was done to allow a fair comparison of the VA gain. The statistical analysis of the VA gain was calculated using a bootstrap, as this data is non-parametric.

2.6. Ongoing additional protocols

In addition to the behavioural analysis, we investigated, through eye tracking analysis using the Tobii X2-60® system, the facial exploration mechanisms used by the participants during the visual and visuo-auditory condition, to identify differences in the exploration strategies between these two V and AV conditions when discriminating a question from a statement.

3. Results

3.1. Behavioural analysis across conditions and groups

Based on our strategy of minimizing the visual information (for both NHS and CIP) and degrading the auditory information (for NHS) the behavioural data retrieved from CI patients and NHS leads to an absence of statistical difference between the two groups concerning their unimodal performances, according to our mixed effect linear model (visual condition: t-value=0.4748, p= 0.0821; auditory condition: t-value=0.4748, p= 0.667; visuo-auditory condition: t-value=0.4748, p= 0.717). Therefore our two groups of subjects have similar performances and this enables a more robust comparison of the visuo-auditory gain. In addition, our results show a non-significant (p= 0.667) tendency, for CI patients to have a lower performance rate in the visual condition (69%) compared with NHS (79%) – see figure 1.
This indicated that, contrary to our previous hypothesis, CI patients do not necessarily have better visual capacities concerning the identification of visual prosodic cues, In addition we observed that 74% of CI patients were better in the auditory condition than in the visual condition (26%) a proportion that differ from that observed in NHS. In NHS only 60% are better performers in auditory discrimination vs. 40% for the visual condition.

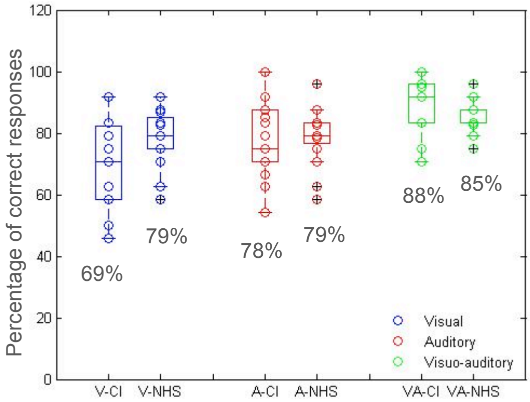


Figure 1: *CI patients and NHS performances with data spread and mean performance for each condition.*

Nonetheless, we observe a strong variability in CI patients for the unimodal conditions, due to the large spread of data observed (Figure 1). A variance analysis carried out reveals a significant variability in CI patients ($p<0.05$) not observed in NHS. This variance observed in CI patients in the V only condition reduces significantly compared to the variability obtained in the bimodal (VA) condition. This significant difference suggests that CI patients have benefits of multisensory integration when faced with a bimodal stimulus that enables a significant reduction in the variability, suggesting a decrease in ambiguity of the information used to make the decision.

3.2. The visual auditory gain: a fusion between vision and hearing

In both groups, the bimodal presentation induced an increase of performances (see fig) in agreement with the well-known perceptual benefits of multisensory integration. As the unimodal performances were similar in both groups, calculating the VA gain allows to us to observe if NHS and CIP differ with respect to bimodal integration for prosodic stimuli. Figure 2 shows VA gain values for CI patients and NHS. The bootstrap analysis carried out on this data reveals a significant difference within the CI patient group and between CI patients and NHS as the confidence intervals do not overlap between these two groups. CIP have a MS gain, which is about 4 times greater to that observed in NHS (13.4 vs 3.2%). Of importance the MS gain observed in NHS do not reach the significant level. Altogether these results highly suggest the presence of a strong skill in CIP to integrate visual and auditory prosodic information.

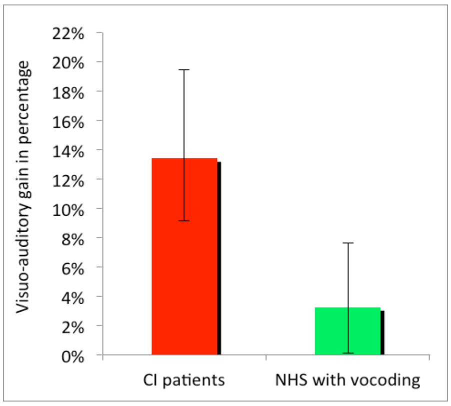


Figure 2: *The VA gain for CI patients and NHS with confidence interval values.*

3.3. Preliminary eye tracking data

Since CI patients did not demonstrate better visual capacities to aid in the discrimination between a question and a statement based on visual prosodic cues, this study was prolonged with eye-tracking data, in order to see how CI patients and NHS explore the face to aid in this distinction.

For this preliminary data, 10 NHS were tested and the total number of fixations in the different visual regions of interest was calculated. Whilst comparing the visual and the visuo-auditory condition we can observe a slightly more important tendency for NHS to fixate on the eyes 22,4% during the visual condition vs. 18.28% for the visuo-auditory condition. However this result is not currently significant. The heat map below shows the difference between the fixation patterns of 2 CI patients and NHS for the visual only condition for both a question and a statement.

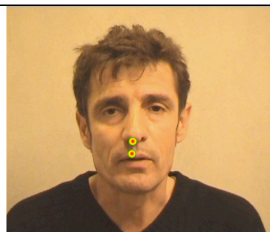
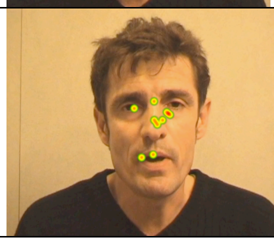
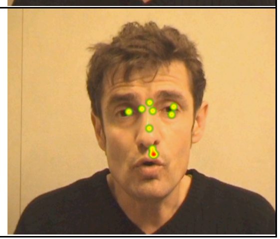
	Statement	Question
CIP		
NHS		

Figure 3: *Fixation patterns for two CI patients and NHS during the visual condition*

The two CI patients currently recruited tend to show a clear preference for the lower half of the face. These results suggest that CI patient automatically are engaged in a lip-reading task in spite that they have been provided by the written sentence before the video presentation, and that sentence comprehension was not an issue to perform the tak. However more data are necessary to confirm that CI patient present an abnormal face exploration during prosodic cues discrimination.

4. Discussion

4.1. Multisensory integration in speech

It is a widely known phenomenon, that the visual sensory channel enhances auditory speech perception, in a noisy environment as a result of multisensory integration (MSI); the visual and auditory information are complementary and can be fused to enable better speech discrimination in noise. CI patients also rely on MSI to enhance speech perception to disambiguate the degraded auditory information brought by the implant. Rouger et al. (2007) [3], demonstrated that, post cochlear implantation, patients rapidly obtain good speech comprehension in bimodal stimulation (between 80% and 100%) compared to unimodal performances. Concerning, linguistic prosodic cues, we proposed that a similar phenomenon can occur in CIP. In accordance with our hypothesis, visual and auditory prosodic cues are complementary and when presented together enable a VA gain, as evidenced by our results. Indeed, the presence of a bimodal stimulation inherently reduces the ambiguity that a unimodal stimulus can contain, due to the presence of redundant prosodic cues. Our results support the presence of a multisensory integration in CI patients as we observed significantly better performances in the bimodal condition and a significant MS gain of 13% suggesting a cross-modal interaction between visual and auditory prosodic cues. On the opposite, in NHS such benefit is weak and non-significant that could be explain by a ceiling effect. According to the inverted effectiveness rule, we expect to have higher MS gain in NHS in more difficult unimodal conditions.

4.2. CI patients and visual cues

It is often assumed that CI patients have supra-normal visual capacities due to their impaired auditory skills. However, CI patients, contrary to prior beliefs, do not have supranormal visual prosodic discrimination skills in our experimental difficult conditions. Indeed, our results show that they even have slightly lower (non- significant) performances in the visual unimodal condition than NHS (69% vs 79%); The primary hypothesis of such result is that distinguishing a statement from a question is not a meaningful and logic task for CI patients. To distinguish such differences in their everyday life they probably rely mainly on grammatical and syntactic cues. Secondly, it could be hypothesised that CI patients have a different oculomotor behaviour when facing a speaking person. We hypothesize that CIP present a systematic bias of face exploration towards the lower half of the face, due to their enhanced and probably automatic, speech-reading skills. Such behaviour, present in our restricted set of patients, may harm CI patients in the treatment of visual prosodic cues because these cues tend to be associated with eyebrow movements, head movements etc.. As CI patients focalise their attention on the lips they may not perceive these visual prosodic cues that aid in identifying a question from a statement. Research on congenitally deaf individuals that communicate through sign language have shown, through eye tracking analysis, that these patients tend to fixate the nose and mouth region, and have better peripheral vision to discriminate sign language information [17]–[19]. Such skill is probably absent in adult CI deaf patients.

4.3. CI patients have a higher multisensory gain

The multisensory gain, or VA gain, observed for speech perception [3] and prosodic discrimination due to the redundant information, is interpreted as a reduction of the ambiguity that a unimodal stimulus can contain. Our results support the presence of a significantly higher multisensory integration in CI patients than NHS. During the prolonged period of deafness CI patients have developed a compensatory strategy based on the visual channel. After cochlear implantation CI patients rely again more on visual information to compensate for the distorted/impoverished auditory information provided by the implant. We postulate that CI patients are better multisensory integrators for prosodic information because this A-V fusion appears to be independent of their visual skills as, in our experimental protocol, they are not better than NHS during the visual only discrimination tasks. These results complement those obtained by Rouger et al. (2007) [3] regarding speech comprehension. Post cochlear implantation, patients rapidly obtain better AV speech comprehension performances compared to NHS evaluated with a simulation of a cochlear implant. CI patients are therefore superior cross modal integrators since they use the redundant prosodic and speech cues to better treat bimodal stimuli. This supra-normal multisensory integration capacity that CI patients appear to have is dependent on a strong audio-visual synergy, which has previously been demonstrated at the brain level [20], [21].

5. Conclusions

Linguistic prosody is not only an auditory stimulus but also a visual one. The auditory prosodic cues, which are badly restituted by the cochlear implant processor, are badly discriminated by CI deaf patients. However, this perceptual deficit of auditory prosody is well compensated by the supra-normal skills of CI patients to fuse the visual and auditory prosodic information. This suggests the presence of enhanced synergy between auditory and visual cues in CI patients, as a compensation mechanism, can be generalized for linguistic and non-linguist information.

Regarding the visual exploration of a talking face by a CI patients, our preliminary data require further investigation to understand how these patients can extract the visual prosodic information according to a different strategy that that observed in hearing subjects.

6. Acknowledgements

We would like to thank the CI patients and NH subjects for their participation, ML. Laborde, C. Algans and M. Tartayre for their help in the recruitment process, and the ENT service for their support.

This work was supported by ANR Archicore (ANR-14-CE13-0033-02) and ANR VirtualHearing3D (ANR-16-CE17-0016-03), and recurrent funding of the CNRS.

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